Nancy Grace Roman Space Telescope Grism and Prism: Optical Design

Guangjun Gao[1*], Bert A. Pasquale[1], Qian Gong[1], Catherine T. Marx[1], Margaret Z. Dominguez[1], Bente H. Eegholm[1], Laurie Seide[2], John G. Hagopian[1], John P. Lehan[1], Victor J. Chambers[1], and Joshua Schlieder[1]

1. NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA
2. KBR Inc, 8120 Maple Lawn Blvd., Fulton, MD 20759, USA
guangjun.gao@nasa.gov

Abstract: The Grism and Prism are two slitless spectroscopic instruments which provide higher (R:500~900) and lower (R:75~170) dispersion spectra. The design methodology, as-designed performance and Monte Carlo simulations results are presented.

1. Introduction

The Roman Observatory, a flagship project of NASA, is designed to enable fundamental discoveries in the areas of dark energy, exoplanets, and infrared astrophysics. The Roman Observatory consists of a 2.4m Three Mirror Anastigmat (TMA) telescope and two instrument benches: the Coronagraph Instrument (CGI) and the Wide Field Instrument (WFI), see Fig.1. The WFI bench, located after the telescope Aft Optics Module, carries the Focal Plane Assembly (FPA) featuring a smile-shaped detector array composed of 18 4k x 4k HgCdTe sensor chips. The Element Wheel Assembly (EWA) features eight bandpass filters covering wavelengths from the visible to NIR, a Grism for higher dispersion imaging spectroscopy, and a Prism for lower dispersion imaging spectroscopy. The combination of the high-resolution detector array and the TMA's flat-field optical design enables the Roman Observatory to capture images with resolution comparable to Hubble, but with a field of view roughly 100 times larger. The Grism and Prism are slitless, multi-object spectroscopic imaging instruments that enable analysis of a large number of celestial objects simultaneously.

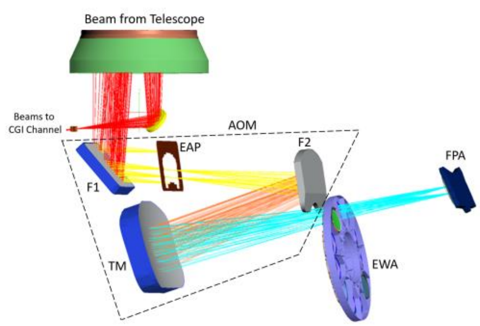


Fig.1. Layout of WFI channel optics.

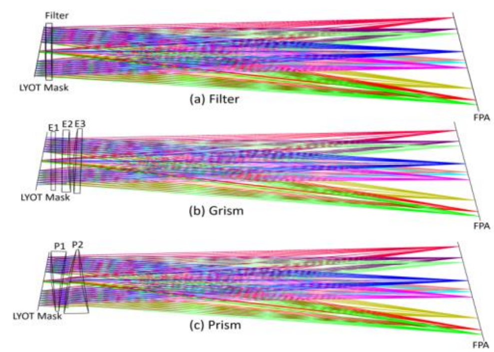


Fig.2. Position of Filters, Grism, and Prism relative to FPA when in use.

2. Optical Design of Grism and Prism

2.1 Design Considerations and Aberration Balancing

To maximize observational efficiency and minimize size, the EWA-mounted Grism, Prism, and Filters are near the telescope exit pupil, and each must relay the telescope image to the same focal plane faithfully, as shown in Fig.2.

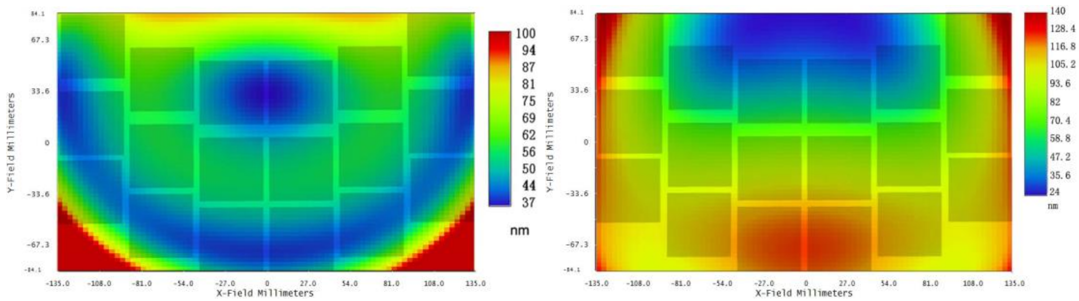
In many applications, dispersive elements are located in collimated or very slow beams to reduce aberrations [1,2]; however, in the Roman Observatory the EWA elements are designed to be located in the telescope's converging beam. This requires careful aberration balancing between the sub-system's surfaces since either a single glass flat element (like E1 of Grism) or wedged prism (like P1 of Prism) in a convergent beam will introduce aberrations like defocus, spherical aberration, coma and astigmatism [3]. At least one additional prism is also needed to compensate the chief ray deviation caused by the main dispersive element. For the Grism, a diffractive optical element E1 disperses the wavelengths, and elements E2 and E3 are used to balance the field aberrations caused by E1 while maintaining zero net chief ray deviation. Similarly in the Prism, P1 is the dispersive element, and P2 is used to balance the aberrations and restore the chief ray direction. Except for Grism element E1, the radii of curvatures of all other Grism and Prism elements are also used as variables to balance aberrations and control overall optical power.

Only spherical surfaces were selected to avoid the added complexity of fabricating conic or aspheric surfaces.

For the Grism, Suprasil-3001 was selected for all elements due to its low thermal expansion coefficient (CTE=5e-7/K), small thermal variation in refractive index, good transmission over designed wavelength band, and excellent radiation hardness. For the Prism, the high index glass S-TIH1 is used for P1, while the much lower dispersion material CaF2 is used for P2.

2.2 Design Results

The optimization merit function for the Grism and Prism included image quality, spectral resolution, chief ray deviation, some constraints for element shape, relative distance, etc. After numerous design iterations and trades, the resultant performance of the flight Grism and Prism are shown in Fig.3 (a) and (b).

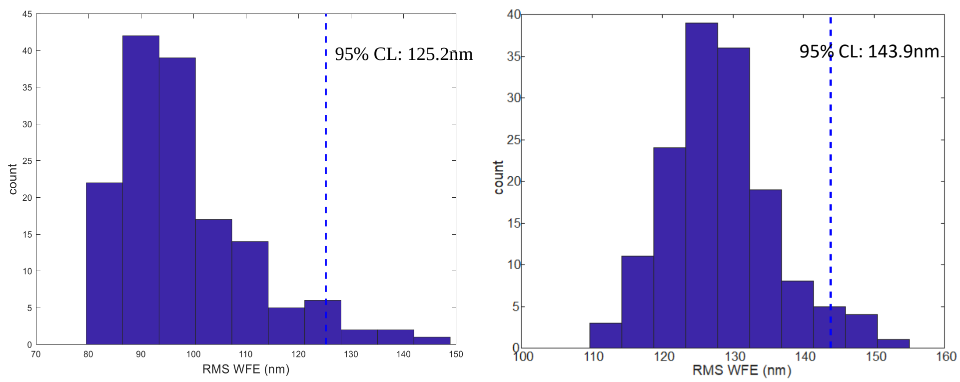


(a) (b)

Fig.3. RMS wavefront error distribution across the FPA at evaluated wavelength (a) 1550nm for Grism and (b) 1200nm for Prism. The 18 squares represent the Sensor Chip Assemblies positions. Per specifications, 95% of the FPA fields of Grism have RMS WFE less than 67.2nm, and 90% of FPA fields of Prism have RMS WFE less than 121nm.

2.3 Tolerance Analysis and Monte Carlo Simulations

To estimate the on-orbit performance of the Grism and Prism, we performed Monte Carlo simulations with independent sub-steps for ambient fabrication, alignment, and for orbital cool-down. In the orbital cool-down step, our Monte Carlo simulation required cold Grism/Prism models. These cold models were inserted into the perturbed telescope models generated by the Monte Carlo process. These merged models were used to predict the as-built observatory performance in the spectroscopic modes. We performed 150 Monte Carlo trials for both the Grism and Prism assemblies. The wavefront error results are presented in Fig. 4 (a) and (b). Monte Carlo simulations suggest that we can meet the Observatory on-orbit WFE requirements (159.45nm Grism, 160nm Prism) at the 95% confidence level (CL) while maintaining the required margin.



(a) (b)

Fig.4 RMS WFE Histograms from Monte Carlo simulations of the (a) Grism and (b) Prism

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